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# Erbium Laser Ablation of Dental Hard Tissue: Effect of Water Cooling

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***Background and Objective:*** **Several lasers have been explored for hard dental tissue applications; used alone they have resulted in potentially harmful temperature increases in the pulp chamber.**
***Materials and Methods:*** **An Er:YAG laser ($\lambda$ = 2.94 μm) was used to ablate hard dental tissues. Ablation rates with and without a water-cooling spray were measured. Subsequent experiments investigated the cooling effects of the water. Initially single channels were drilled into dentin; further studies involved ablating rectangular areas with repetition rates up to 10 Hz.**
***Results:*** **The water spray minimally reduced the ablation rates of dentin and did not affect the ablation rates of enamel. The water spray effectively cooled the teeth; while using the maximum average power investigated (10 Hz, 360 mJ/pulse), a water flow rate of 4.5 ml/min limited the temperature rise in the pulp chamber to less than 3°C.**
***Conclusion:*** **The studies confirm the feasibility of using an Er:YAG laser in conjunction with a water spray to safely and effectively remove hard dental tissues.** © 1996 Wiley-Liss, Inc.

Key words: **dentin, dentistry, enamel, Er:YAG laser, teeth, temperature**

## INTRODUCTION

Several infrared lasers have been explored for use in dentistry, including $CO_2$, Nd:YAG, Ho:YAG, and Er:YAG lasers [1–10]. Initial studies of Er:YAG laser ablation of hard dental tissues were performed by Hibst and Keller, who measured the depth of ablation in dentin and enamel after delivering 10 pulses of laser radiation at various energy levels [4,6]. Li et al. determined the ablation rates of these materials as well but expanded the fluence range up to approximately 140 J/cm$^2$ and also explored two different repetition rates, 2 and 5 Hz [7]. These investigators and others have shown that erbium lasers readily ablate hard biological tissues such as dentin, enamel, and bone with thermal damage zones no greater than approximately 50 μm [6,11–14].

Effective laser ablation of biological tissues with infrared lasers is largely dependent on the presence of water. Infrared radiation couples into water molecules, causing an increase in the vibration of the molecules and increasing the temperature and pressure within the tissue. Ablation is initiated as an explosive thermal event. Effective ablation of dental hard tissues is possible with erbium lasers despite the limited water content of these tissues; however, the temperature rise induced in the remaining tissue following ablation may be damaging. The zone of thermal damage surrounding ablation craters has been well studied [6,11–14]. Less attention has been given to laser-induced thermal damage that may occur at depth in tissue and that may not be visible in tissue sections obtained immediately after laser ablation. For example, it has been shown that the enamel and dentin layers in teeth can withstand a relatively large thermal insult compared with the temperature-sensitive pulp chamber [15,16]. Prevention of damaging temperature rises in the pulp chamber is critical for safe removal of dental tissues. In a study performed on an animal model,

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an external heat source was applied to teeth, producing various temperature increases in the pulp [16]. Following a pulpal temperature rise of 5.6°C, 15% of the teeth necrosed. The necrosis rate rose to 60% with a temperature rise of 11.1°C and near 100% with an increase of 16.7°C. For a laser-based dental procedure to be safe, it appears that the temperature rise within the pulp must be less than 5°C.

Optimal ablation conditions would limit the thermal damage at the ablation site and also the damage to underlying structures. Water has been used as a cooling agent with a variety of dental lasers [2,3,17,18]. To date no studies have quantified the ablation and thermal effects of Er:YAG laser irradiation of dental tissues under the influence of a cooling water spray. Both single spot and larger area ablations were performed. Clinically relevant procedures are caries removals as well as surface preparations in anticipation of crowns and bridges. Dental hard tissues were used in this study; however, the concept of water cooling may be equally applicable to bone and possibly soft tissues.

## MATERIALS AND METHODS

### Ablation Rate Studies

An Er:YAG laser (Schwartz Electro-Optics, model 1-2-3) emitting approximately 230-μs–long pulses of 2.94-μm radiation was used to determine the ablation rate of dentin and enamel. The laser radiation was focused with a 10-cm focal length $CaF_2$ biconvex lens onto tissue samples of measured thickness. The number of laser pulses required to perforate the samples was counted. The repetition rate was kept constant at 2 Hz throughout the ablation rate study. The energy was varied from approximately ablation threshold levels up to a maximum of 400 mJ per pulse. The pulse-to-pulse stability of the laser was on the order of 5%. The beam profile was measured by scanning a 25-μm diameter pin-hole aperture through the beam path. The beam diameter was approximately 0.7 mm (1/e) with a profile of roughly $TEM_{10}$, resulting in fluences ranging up to 110 J/cm$^2$. The 1/e diameter value was computed to facilitate comparison of the results with the literature.

A cooling water spray was incident on the samples from an off-axis position relative to the laser radiation and was directed at the ablation site. The flow rate of the water spray was selectable in discrete steps from 0 to 11 ml/min. The temperature of the supply water remained at ambient room temperature, approximately 20–23°C.

The tissue samples were derived from extracted adult human molars and premolars. Immediately following extraction, the teeth were placed in ordinary tap water to which a small amount of bleach was added to disinfect the samples. The time from extraction to experimentation varied considerably, with the maximum being several weeks. Only healthy-appearing teeth with no obvious defects or caries were used for experimentation. Transverse sections, approximately 0.5 mm thick, were made with a slow-speed diamond saw under water cooling (Buehler, Isomet 11-1180). Prior to irradiation the sample thickness was measured (±5 μm) using a micrometer (Starrett, Co., #210-A). Penetration of radiation through the sample was detected with a joulemeter (Gentec, ED-200). The average thickness of tissue removed per pulse was calculated. A minimum of nine ablation rates was measured and averaged for each energy level and water flow rate.

### Temperature Studies—Single Spot Irradiation

The primary purpose of the water spray was to cool the tissue during irradiation. The temperature rises induced in the tissues with and without water spray were investigated. A setup similar to the ablation rate studies was used. Transverse sections of teeth were cut to a thickness of 4–5 mm. A 1-mm diameter channel was mechanically drilled from the back side, leaving either 1 or 2 mm of material between the surface and bottom of the channel. The channel was filled with an aqueous gel (Graphic Controls Corp., EKG-Sol) to provide thermal contact between the tooth and a 0.6-mm diameter thermocouple probe, which was inserted into the channel (Omega Corp., TAC-80T/5SC-TT). A simple experiment was performed to prove that the gel provided good thermal contact. A tooth with a probe inserted was partially immersed in a hot water bath and the time-temperature history was recorded. The tooth had nothing, water, or gel filling the channel with the probe. The gel-filled tooth had the quickest rise time (time to reach 90% steady-state temperature), although all rise times were within 20% of each other.

The laser emitted radiation at 2 Hz that was focused as in the ablation rate studies and was directed normal to the front surface of the tooth section such that ablation proceeded toward the thermocouple. The time-temperature history was

recorded on a digital oscilloscope (LeCroy, 9400A), and the number of pulses required to penetrate through the sample to the thermocouple probe was noted. The temperature measuring system had a rise time of approximately 40 ms, an accuracy of ± 1.7°C, and a sensitivity of ± 0.5°C. The relationship between temperature and the distance to the probe was determined from these data. The average amount of tissue ablated per pulse was calculated and used in the following equation:

$$\text{distance to probe after n}^{\text{th}}\text{ pulse} = \text{original distance} - (\text{average ablation rate} \times \text{n}). \quad (1)$$

### Temperature Studies—Area Irradiation

The setup was sightly altered for the area ablation studies. The laser radiation was directed onto whole extracted teeth. Each tooth was mounted onto a computer-controlled X-Y translator that allowed the tooth to be raster scanned in front of the laser beam to form a rectangular ablation pattern. The computer was programmed to create an area of 4.5 × 3.5 mm with a step size approximately one quarter of the spot size and an average of 2.5 pulses per spot. Prior to irradiation a 1-mm diameter channel was drilled mechanically from the occlusal surface of each tooth into approximately the center of the crown. The channel was filled with gel and the thermocouple probe was inserted into the pulp chamber. The probe was connected to an oscilloscope to facilitate measurements of temperature vs. time. The repetition rate of the laser was varied between 2 and 10 Hz. The 1/e beam diameter, energy per pulse, and total energy delivered were maintained at relatively constant values as the repetition rate was varied. Maximum energies of approximately 360 mJ/pulse and a larger spot diameter of 0.9 mm (1/e) were used, yielding a fluence maximum of 57 J/cm$^2$. A minimal water flow rate of 4.5 ml/min was used to cool the samples during irradiation. The entire procedure lasted from 48 seconds to 4 minutes for repetition rates from 10 to 2 Hz, respectively.

### Water Transmission

Photomicrographs of water-cooled teeth were taken to facilitate measurement of the water layer thickness. Sections of teeth were measured with a micrometer. The water layer thickness was calculated (±5 μm) using the ratios of the tooth sections and water-layer thicknesses as measured on the photographs. The transmission of 2.94-μm radiation through the flowing water layer was investigated. Water of various flow rates (5.5–11 ml/min) was directed onto a vertical glass coverslip that was placed at the same focal plane as the teeth. Besides the glass slide, the water was not confined in any way so as to simulate clinical conditions. The energy of the Er:YAG laser radiation passing through the glass and the glass/water combination was measured for various incident laser energy settings and water flow rates. The transmission losses from the glass alone were "subtracted" from the glass and water combination to arrive at the transmission through water only. The transmission through the water (Tw) is then given by

$$T_w = \frac{E_{outw/g}}{E_{inw/g} \times T_g}, \quad (2)$$

where $E_{outw/g}$ = energy out of the water/glass comination, $E_{inw/g}$ is the energy incident on the water/glass, and $T_g$ is the transmission through the glass only. The resulting transmission values were not corrected for reflections at the air, water, and glass interfaces.

## RESULTS

### Ablation Rate Studies

The average ablation rates vs. fluence for four water flow rates in dentin and enamel are plotted in Figures 1 and 2, respectively. The water flowing over the dentin did not significantly decrease the ablation rate at the highest fluence level, approximately 105 J/cm$^2$, as determined by performing an analysis of variance ($P > 0.11$). As the fluence was decreased towards the threshold level, the water began to impede the ablation. The ablation rate in the enamel was not affected by the water spray ($P > 0.36$, ANOVA), excluding the 5.45 ml/min, 60 J/cm$^2$ case. It is interesting to note that at a fluence of approximately 40 J/cm$^2$, ablation through the enamel thickness was not possible without the water spray. At the higher fluences, the ablation rates in dentin (>60 J/cm$^2$) and enamel (>90 J/cm$^2$) were not affected by a change in the water flow rate ($P > 0.45$, ANOVA) despite a twofold increase in flow.

### Temperature Studies—Single Spot Irradiation

A plot of distance to the thermocouple probe vs. temperature rise for single spot irradiation is shown in Figure 3. With no water spray, as the

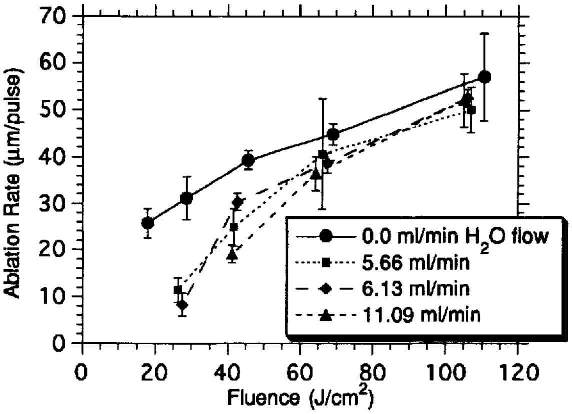


Fig. 1. Ablation rate vs. fluence for dentin. Values are mean ± SD. Note that for fluences of approximately 105 J/cm$^2$ the water did not significantly reduce the ablation rate.

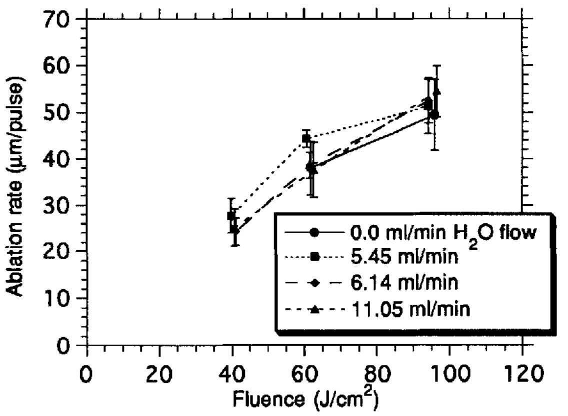


Fig. 2. Ablation rate vs. fluence for enamel. Values are mean ± SD. Note that for a fluence of 40 J/cm$^2$, ablation through 0.5-mm thick enamel was not noted without water.

radiation impinged on the probe the temperature rise reached a maximum of 15°C. With the cooling water spray, the maximum temperature rise was only 2°C. Penetration of 2-mm thick samples was not possible with the addition of the water spray.

### Temperature Studies—Area Irradiation

A plot of the cumulative energy delivered vs. the temperature rise in the area-irradiated teeth is shown in Figure 4. For the samples that were not water cooled, the temperature rise exceeded 15°C by the end of the procedure. With a water spray of 4.5 ml/min, the maximum temperature rise in the teeth was less than 3°C for all repetition rates tested. Photographs of area ablations conducted on the same tooth with and without water cooling are shown in Figure 5. Significant charring of dentin and crystallized debris adherent to the crater walls were seen with no water cooling. Irradiation while water cooling produced cleaner cuts with no charring and little residual debris.

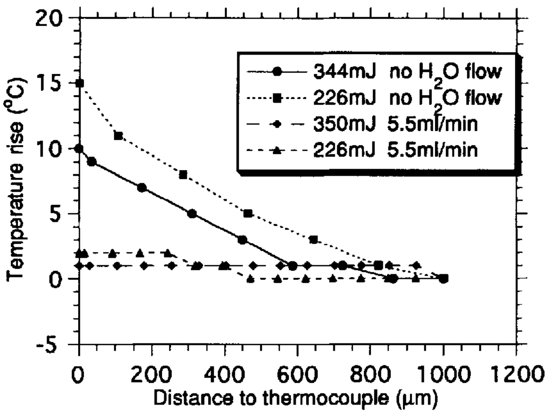


Fig. 3. Temperature rise vs. distance of ablation front to the thermocouple probe for single spot drilling. Initial sample thickness = 1 mm, repetition rate = 2 Hz. Note that during ablation the distance to the thermocouple probe decreases from 1,000 µm to 0 µm.

### Water Transmission

The thickness of the water layer flowing over the teeth was estimated from photographs to vary between approximately 200 and 600 µm. The photographs indicate that the flow rate did not substantially affect the water layer thickness. A plot of the transmission of Er:YAG laser radiation versus incident energy is shown in Figure 6. A maximum of 96% transmission through the water flowing over the glass slide was achieved with the highest fluence of 55 J/cm$^2$. The transmission dropped to 67% with an incident fluence of 10 J/cm$^2$.

## DISCUSSION

### Ablation Rate Studies

The results of the ablation rate studies show that ablation through a flowing water stream was quite effective. As previously stated, quantitative measures of the Er:YAG laser ablation of dental materials through water have not been found in the literature. A comparison of our ablation rates of dry dentin and enamel to those reported in the literature indicates that our rates were moderately lower for dentin and similar for enamel [4,7]. Differences in results can be explained by examining the methods of experimentation. Whereas Hibst and Keller used a constant num-

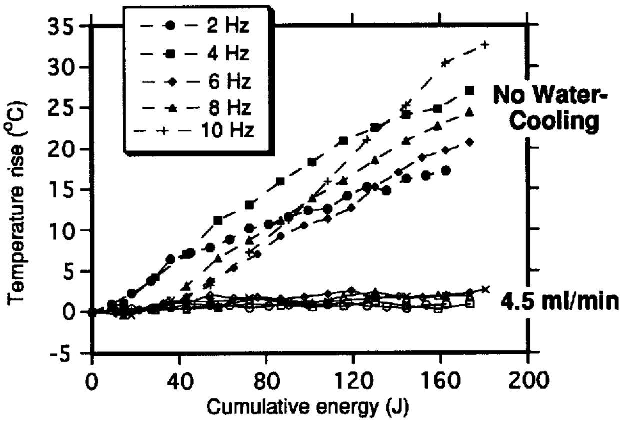


Fig. 4. Temperature rise in the pulp chamber vs. cumulative energy delivered during area ablation, with and without water cooling. Pulse energy was 360 mJ; area ablated was 3.5 × 4.5 mm.

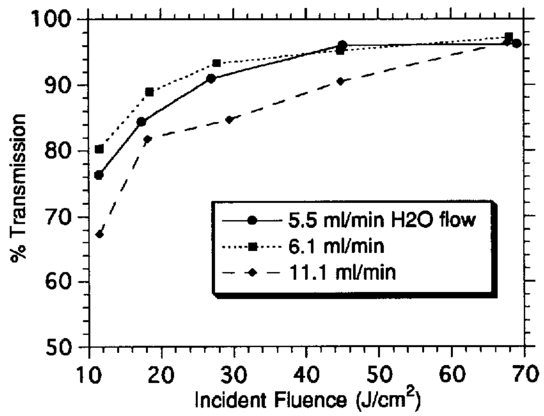


Fig. 6. Transmission of Er:YAG laser radiation through water, flowing at various rates over a glass coverslip, vs. incident fluence.

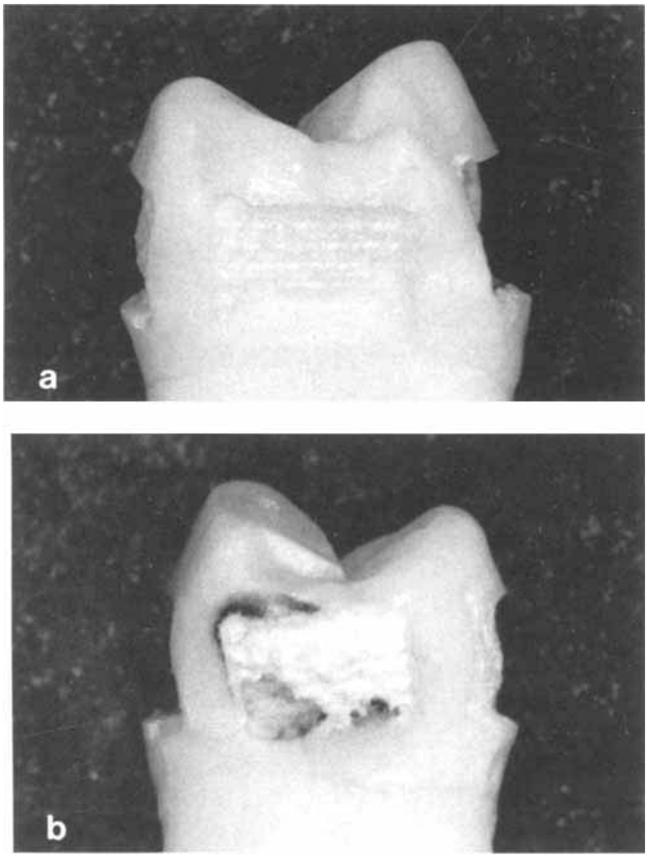


Fig. 5. Photographs of a tooth irradiated (**a**) with and (**b**) without water cooling (4.5 ml/min). The area ablated is approximately 4.5 × 3.5 mm. Irradiation parameters were 360 mJ/pulse, 8 Hz, 173 J delivered, 1/e beam diameter ≈900 μm.

ber of pulses (10) to determine the ablation rates, we chose to use a relatively consistent sample thickness, which generally required more than 10 pulses to penetrate. Hibst and Keller showed that the ablation rate decreased as the number of pulses delivered increased, which possibly explains why their ablation rates were higher.

It is counterintuitive to expect significant 2.94-μm radiation to penetrate through water; however, a relative transmission of 96% was achieved. The significant transmission seen through water was likely the result of cavitation. Cavitation occurs when the initial portions of the laser pulse are absorbed by the water and the pressure in the water rises and pushes the water stream out of the beam path [19]. Cavitation can explain how significant transmission through water can occur, and subsequently why the ablation rate is relatively unaffected by water, particularly when using high fluences. The use of the glass slide in the transmission calculation experiment was meant to produce the same pattern as water flowing over teeth. Incongruities could have resulted from the manner in which water flows over these differing materials. The transmission values were not corrected for reflections at the interfaces because the water surface was highly irregular and continually varied as the water flowed.

As seen in Figures 1 and 2, despite a twofold increase in the water flow rate, the ablation rates in dentin and enamel using the higher fluences were not significantly different among the water-cooled samples. However, using the lowest fluences and a flow rate of 11 ml/min or higher, ablation occurred only with infrequent random laser pulses. Penetration of the 1-mm thick samples was not seen after delivering several hundred pulses. The pulses that did ablate were likely

due to a thinner sheet of water temporarily flowing over the surface. At the highest fluences, penetration of 1-mm thick samples was still possible with water flow rates up to 35 ml/min. While attempting to ablate thicker samples, on the order of 2 mm, penetration at any fluence was not possible while utilizing the water spray. As ablation proceeded into the 2-mm thick sample, water flowed into the crater between pulses. As the crater increased in depth, more water was confined in the path of the radiation until ablation of the tissue ceased. This dilemma is not likely to be encountered clinically since there is little occasion to ablate small diameter channels.

As was previously mentioned, ablation through an enamel thickness on the order of 0.5 mm was not possible at low fluences in the absence of a water stream. Although the initial few pulses caused visible ablation, the ablation eventually stalled. This effect was likely the result of dehydrating the tissue with the initial laser pulses; after the water in the surface layer has been removed, the laser radiation can no longer efficiently couple into the tissue [20].

It should be noted that for all experiments the samples were not placed at the focal point but nearer to the lens. Therefore, as ablation proceeded into the samples the effective spot size decreased slightly and the fluence increased. The maximum that the ablation front penetrated in all experiments was on the order of 1 mm; accordingly, the spot size was measured to decrease by 7.5% with a concurrent increase in fluence of 17%. The fluence incident on the initial tissue surface is reported throughout this paper.

### Temperature Studies

The purposes of the thermal studies were, first, to show that the water stream could cool the samples during ablation and, second, to determine the flow rates necessary to ensure safe procedures. Ideally one would want to know the distance between the location of the measured temperature and the surface of the ablation front. This was the goal in the first set of thermal studies in which a single channel was drilled toward the thermocouple probe.

As shown in Figure 3, with water cooling there were only minimal temperature increases; without water cooling the sample temperature increased 10–15°C. The larger temperature rise seen while using the lower pulse energy (226 mJ) occurred because more total energy (more laser pulses) was required to ablate the same thickness of material. This result is expected because it is known that ablation efficiency decreases as pulse energy decreases; thus, more energy goes to tissue heating at lower pulse energies.

The purpose of the repetition rate/area ablation studies was to test the cooling mechanism under conditions that better simulated clinical procedures. In addition to caries removal, the Er:YAG laser may be used for tooth surface preparations in anticipation of crowns and bridges. This was the motivation for performing large-area ablations. Parameters leading to extreme heating conditions were tested: maximal energy and repetition rate, and minimal water flow rate. An increase in the repetition rate up to 10 Hz was made from the previous and clinically impractical rate of 2 Hz. As the repetition rates were increased the beam profiles became more multimode, which also affected the spot size. No attempt was made to maintain a consistent profile; however, the 1/e spot diameter was held constant. Although the setup allowed for quantification and control of all irradiation and cooling parameters, it did not facilitate measurement of the distance from the irradiation surface to the thermocouple probe. Because a variety of teeth were used, the distance from the surface of the tooth to the probe varied from approximately 3.5 to 5.5 mm. The morphology of a tooth plays a critical role in the ablation and heat diffusion, further complicating efforts to compare repetition rate data. Significant differences are seen not only amongst samples but also within a single sample, dependent on the location and direction of incident radiation within the teeth. The sample variabilities were the reason that there was no pattern to the temperature rise vs. the repetition rate. With perfectly matched samples one would expect the final temperature rise to increase as the repetition rate increased. However, from a clinical perspective the important result was that a water flow rate as low as 4.5 ml/min made a significant contribution to the cooling and limited the temperature rises to less than 3°C, well below the assumed safe limit.

One can roughly determine the temperature increase in the water spray required to convect away the heat deposited in a tooth. Based on the data in Figure 4, the temperature of an average-sized tooth weighing 2 grams rose approximately 20°C in approximately 1 minute irradiating at 4, 6, or 8 Hz repetition rates. With a specific heat of 1.5 J $g^{-1}$ °$C^{-1}$ [21], the teeth acquired energy at the rate of 1.0 J/s. The supply water remained at room temperature so that the heat flux was

from the heated tooth towards the flowing water. The energy E, absorbed by a volume of water, V, for a given temperature rise, ΔT, can be calculated from

$$E = \rho c V \Delta T, \tag{3}$$

where ρ is the density (≈1.0 g/cm$^3$) and c is the specific heat (≈4.18 J g$^{-1}$ °C$^{-1}$). For a volume flow rate of 5 ml/min, a temperature rise in the water of only 2.9°C is required to convect 1.0 J/s from the tooth. This calculation is not an attempt at an exact energy balance; it is meant simply to indicate that significant cooling of the teeth can be achieved with relatively small increases in the temperature of the water spray.

The photographs of the ablated teeth also confirmed the value of the water cooling. There was significantly less thermal damage on the surface of the water-cooled samples, which will likely improve bonding of restorative materials compared with noncooled samples.

## CONCLUSIONS

These studies demonstrate the importance of a water spray for cooling laser-ablated tissues. The addition of a fine stream of water directed at the ablation site does not greatly decrease the ablation rate and may even enhance ablation. The water prevents char from forming on the area surrounding the ablation site, indicating a reduced zone of thermal damage surrounding the ablation crater. More importantly, the water spray limits the temperature rises induced in the tissue to less than 3°C. A water spray may have similar beneficial effects on other hard and soft tissues.

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